BNL/PBL SBIR Phase II HTS Program for approaching 40 T

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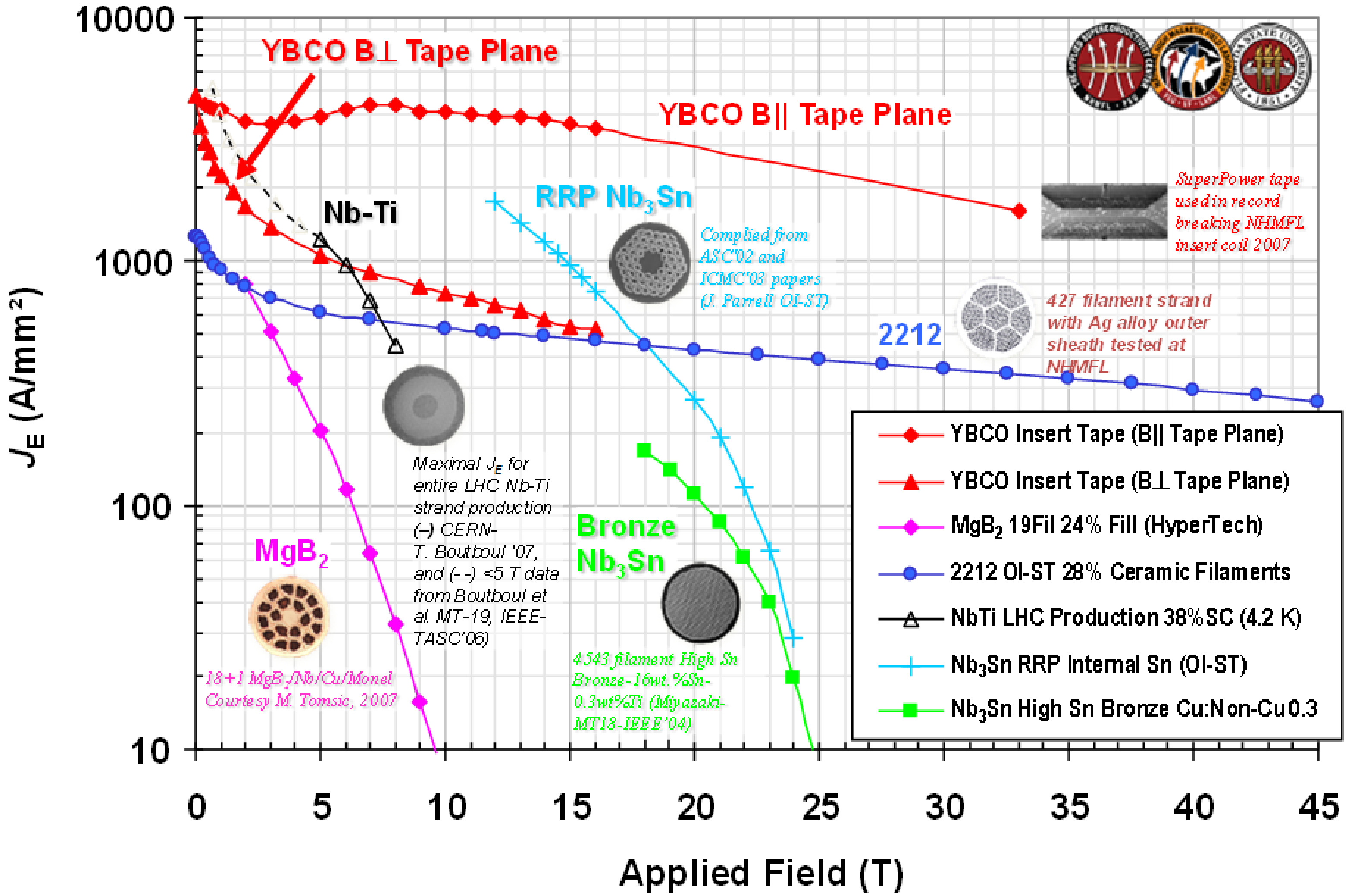
Seminar In FNAL Tech Division   July 22, 2010

- Introduction to YBCO
- BNL RIA/FRIB magnet
- Muon Collider Requirements
- SBIR Program Design
- SBIR Program Progress
- Conclusion

See NFMCC-DOC-553

Introduction to YBCO



- Jc's still very high as B $\longrightarrow$ 40 T
- YBCO Much better than BCCO for direction in long solenoid
- But we must include the angle effect for finite length coils

But

- YBCO comes as single super-conducting layer 4-12 mm wide
- Currents will not flow uniformly over width
- Will have extreme 'magnetization'
- NOT suitable for normal accelerator quality dipoles or quadruples

- But suitable for:

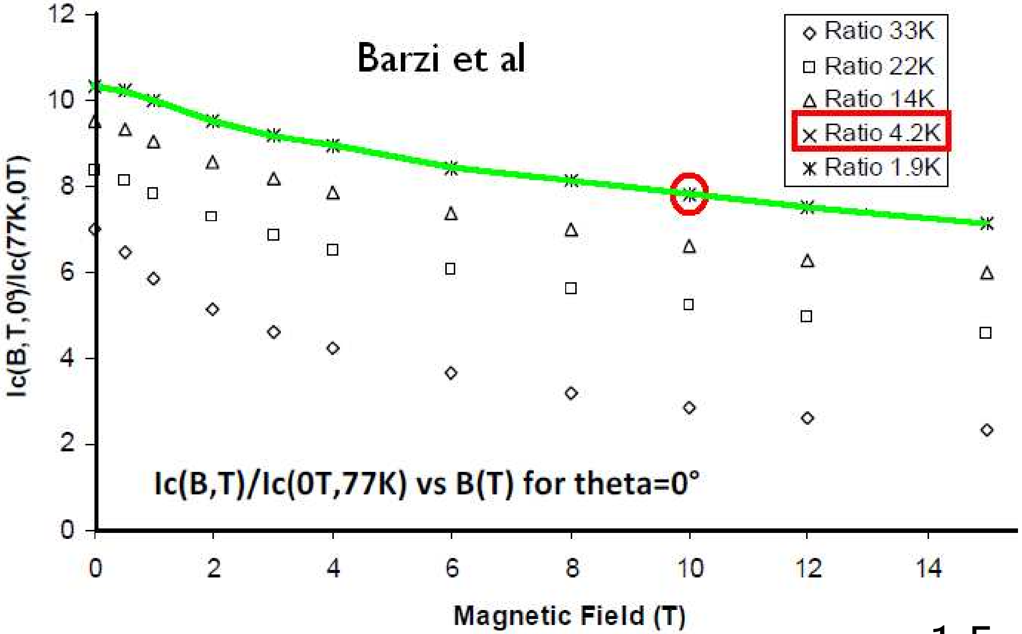
  1. Iron dominated magnets
     e.g Quadruples in very high radiation environments

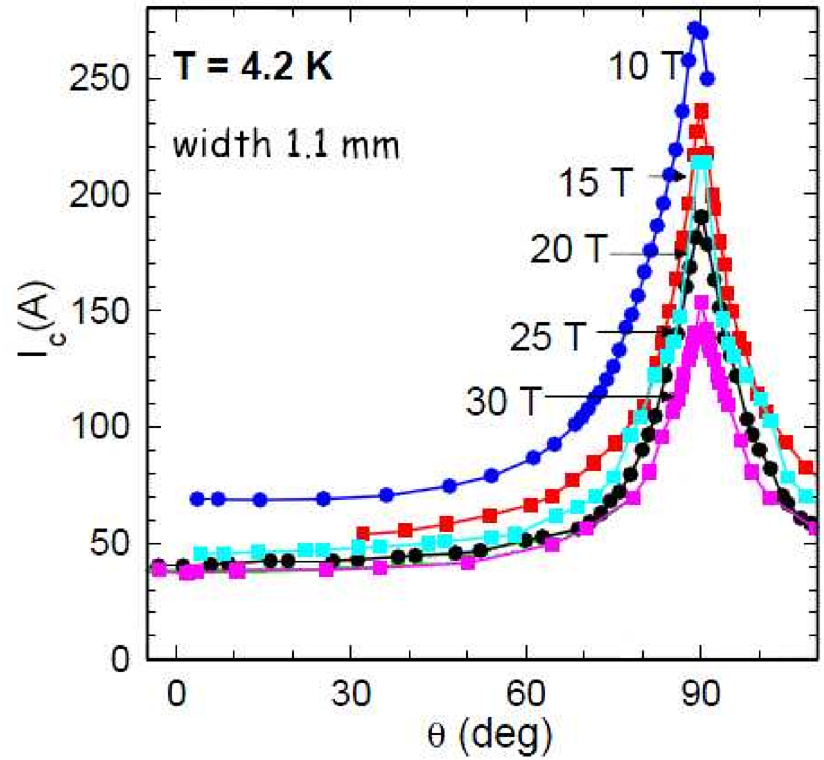
  2. Energy storage devices
     no requirements on field details

  3. Final Cooling solenoids for Muon Collider
     tracks follow field lines wherever they are

- Jc depends on angle between cable and field
  but in a long solenoid the field is in the favorable direction

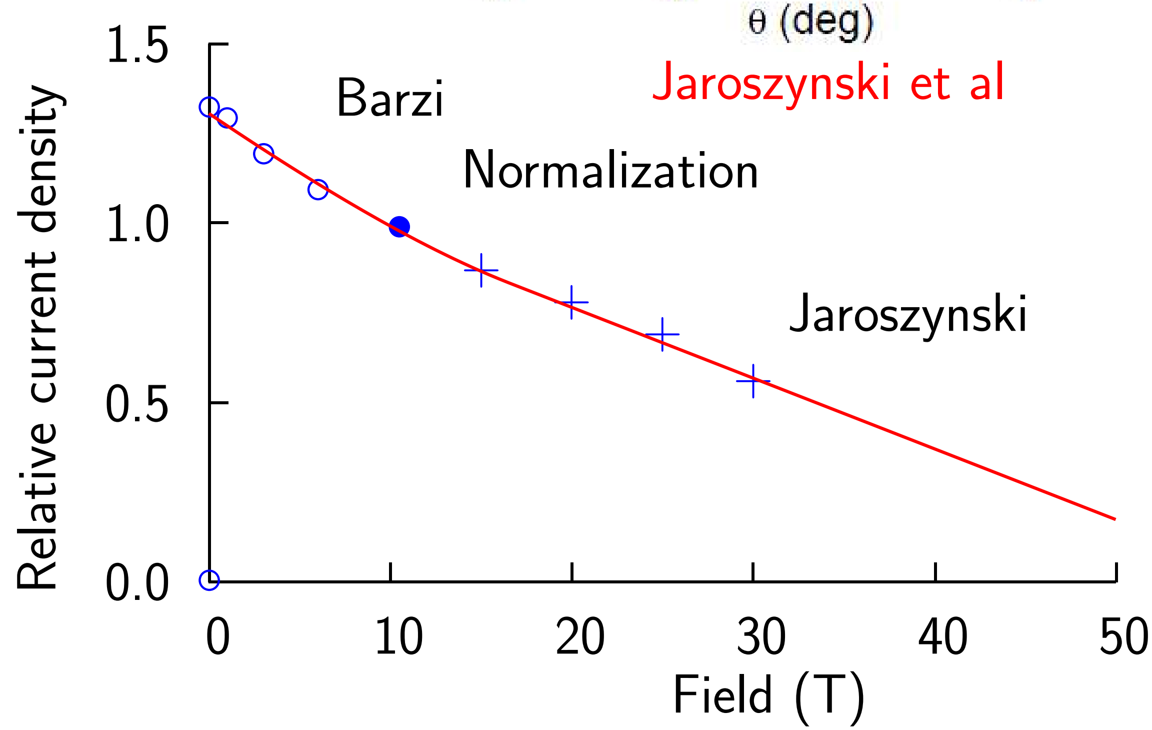
Expression for j vs. B & Angle





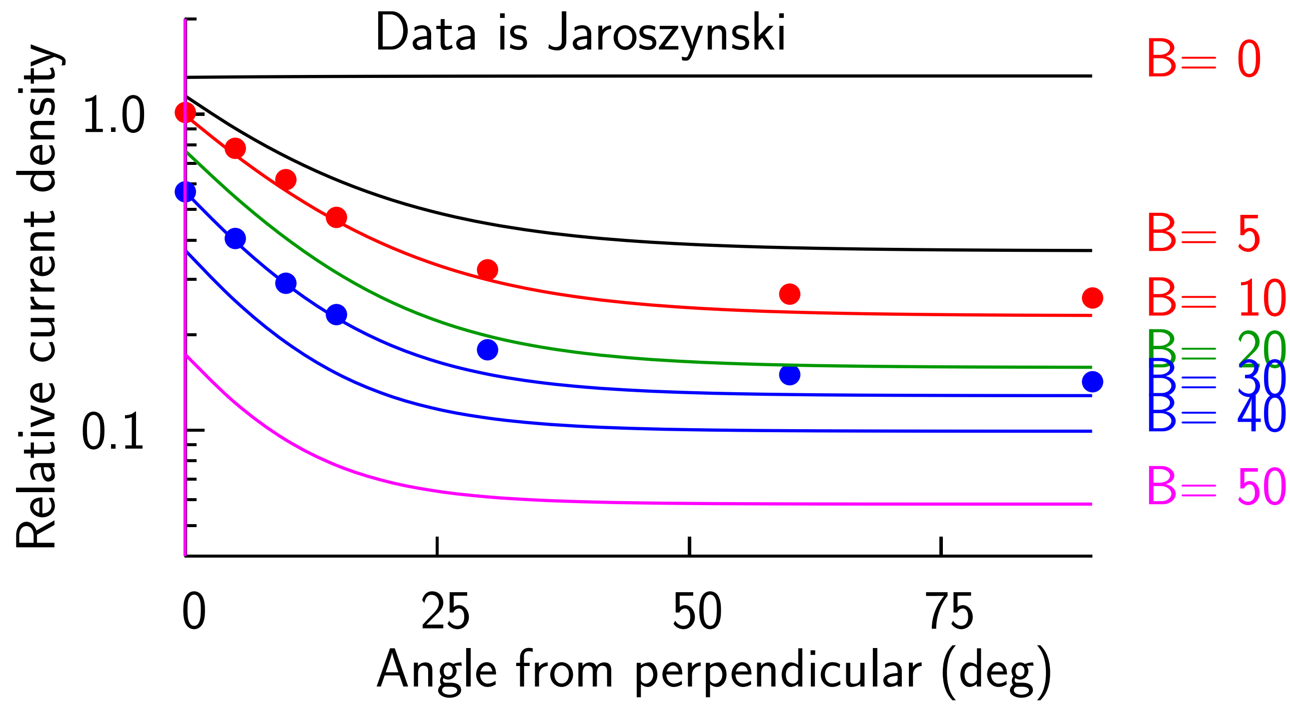
Jaroszynski et al

- 10-30 from Jaroszynski
- 0-10 from Barzi
- Fit to relative current:



Fit Angle dependence & normalize

- Fit to relative angle dependences



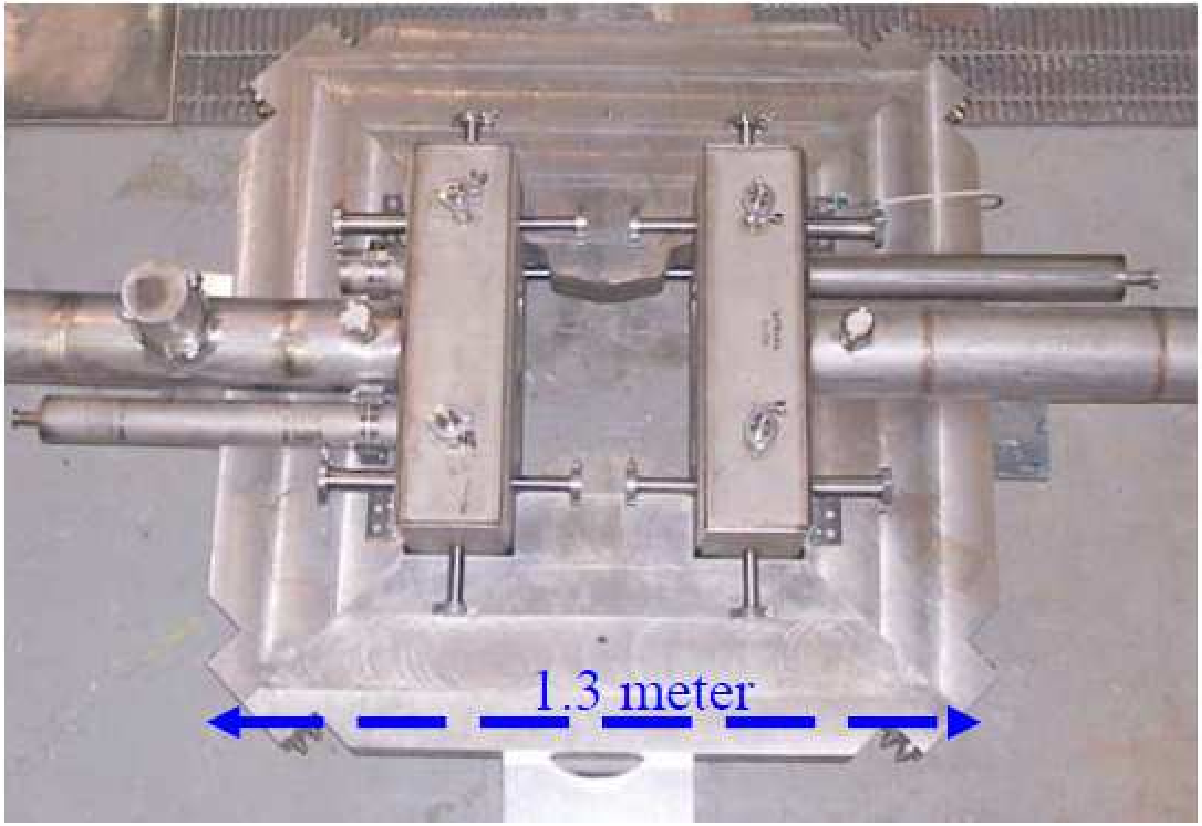
- Absolute normalization from Barzi at 10 T, including insulation

Take 77 deg I= 80 A (rec: 80-115), factor for 10 T 4.4 deg =7.8, margin=20%

$$j(10) = \frac{\overset{\text{I}}{80}\ \ \overset{\text{fac}}{7.8}\ \ \overset{\text{safe}}{0.8}}{(\underset{\text{sc}}{4.} + \underset{\text{ins}}{0.25})(\underset{\text{sc}}{0.1} + \underset{\text{ins}}{.025})} = 939 A/mm^2$$

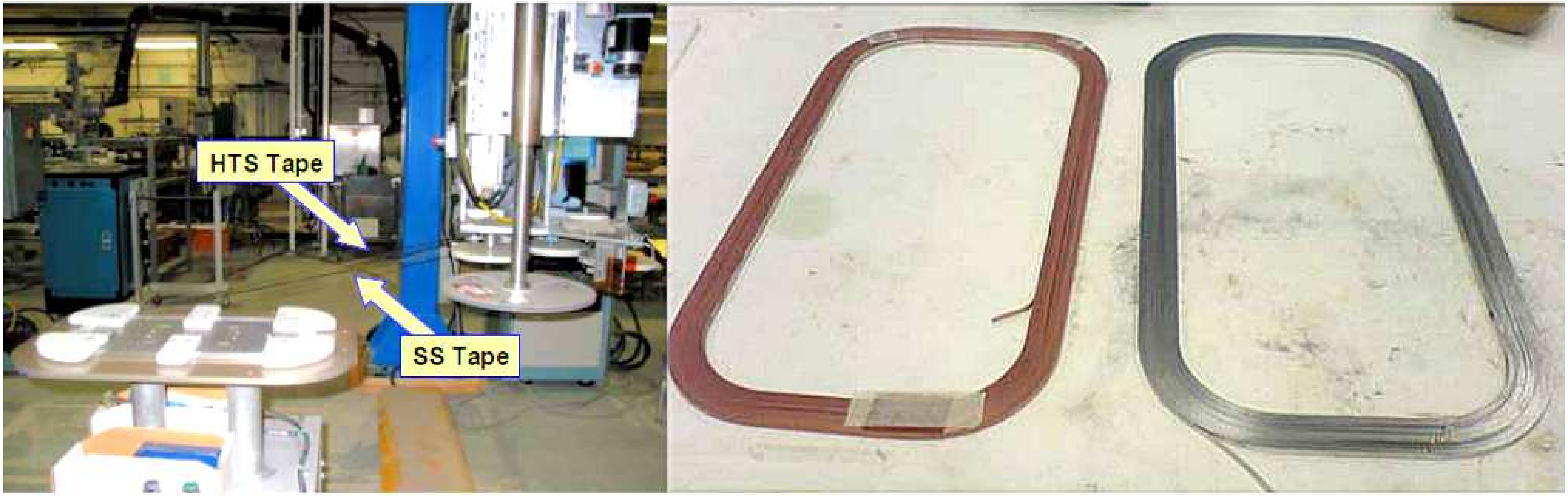
- The resulting dependency is not for the material used, or for any single sample and is used only to get an approximation to actual performance

BNL work on HTS Quadrupole for RIA/FRIB



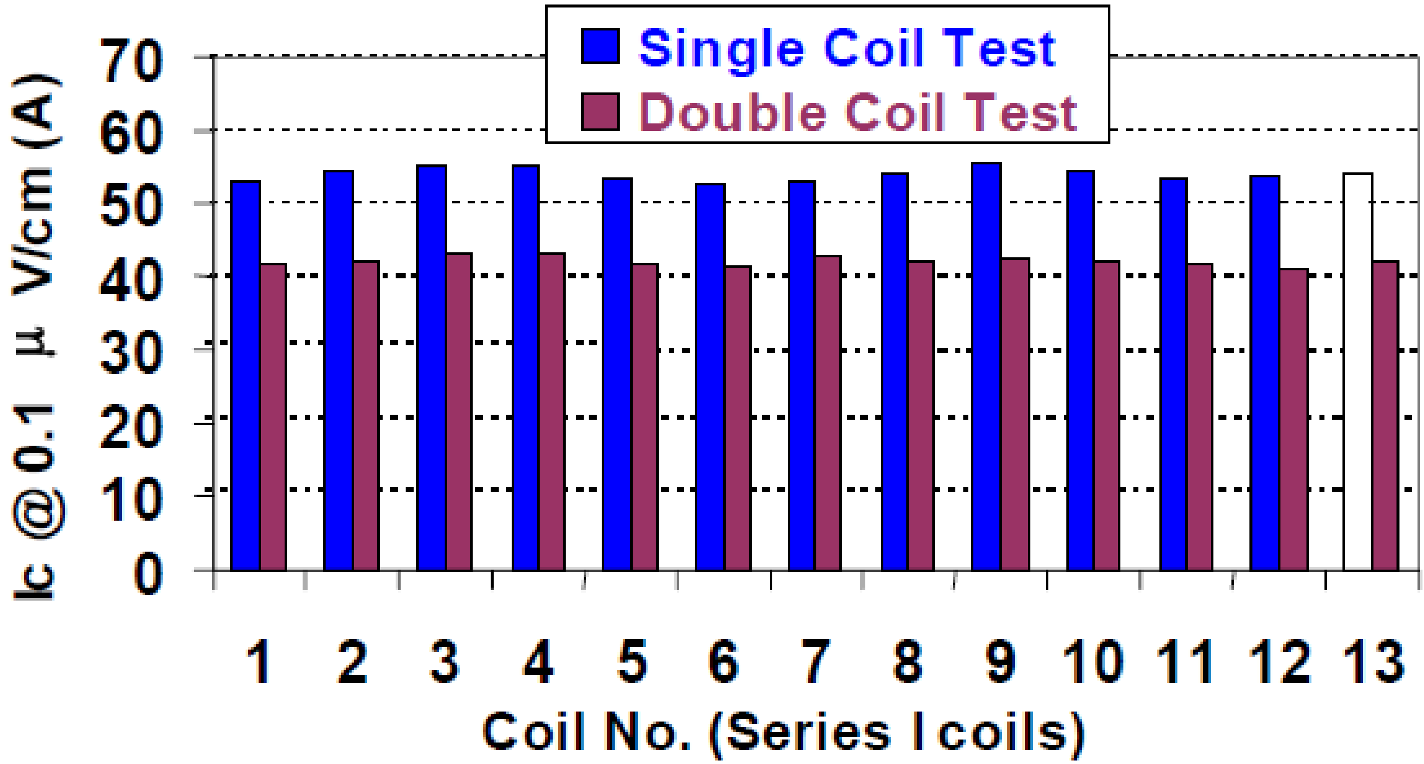
- Iron pole quadrupole built and tested
- Iron is warm
- HTS (BCCO) coils at $\approx$ 70 degrees in cryostats

Winding



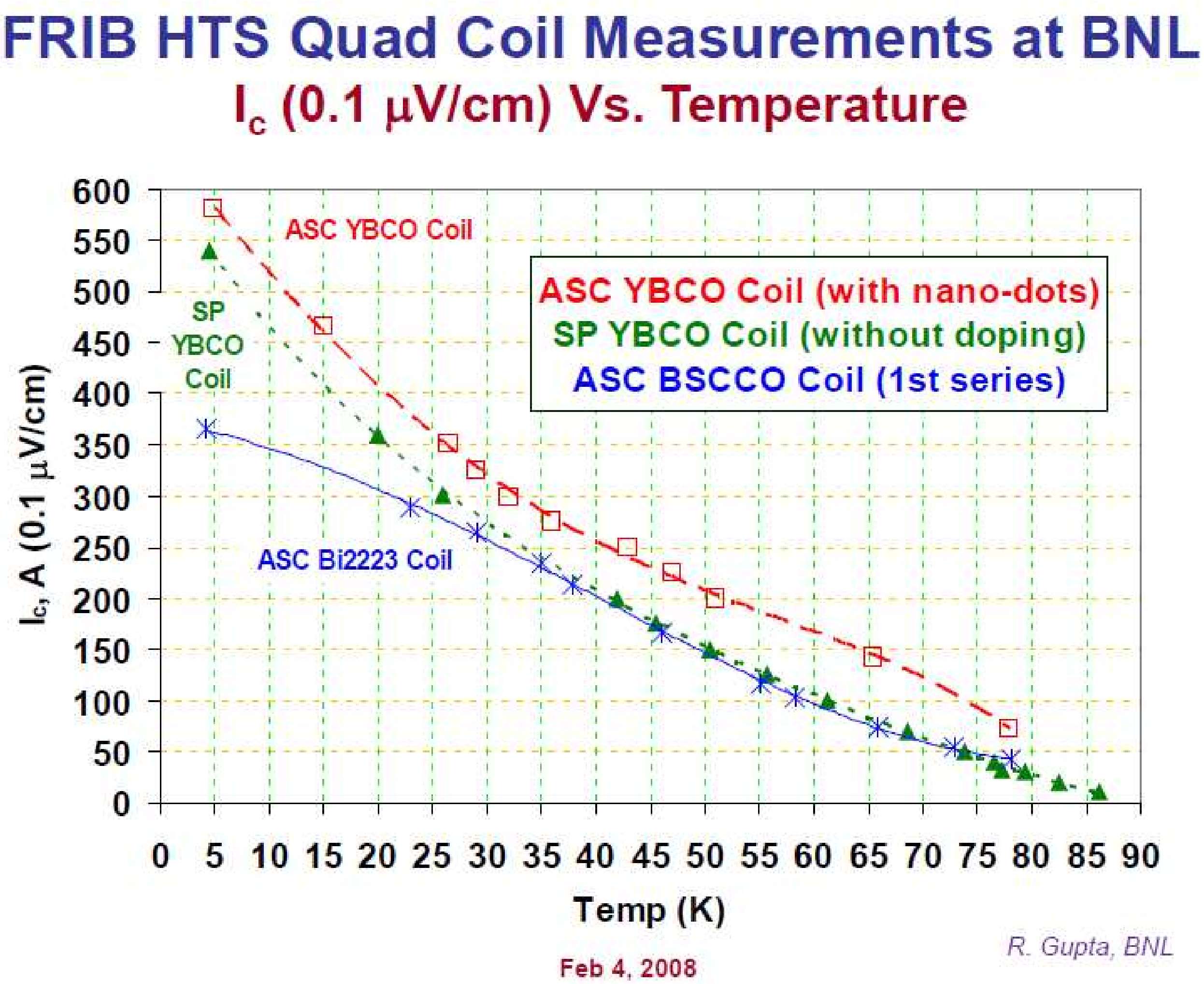
- Stainless steel tape used for 'insulation'
- Because it is radiation hard
- But is also strong and a good enough insulator including for quench protection

Individual HTS BCCO Coil Performance



- Reproducible Performance of many coils

Test of YBCO in RIA Coil

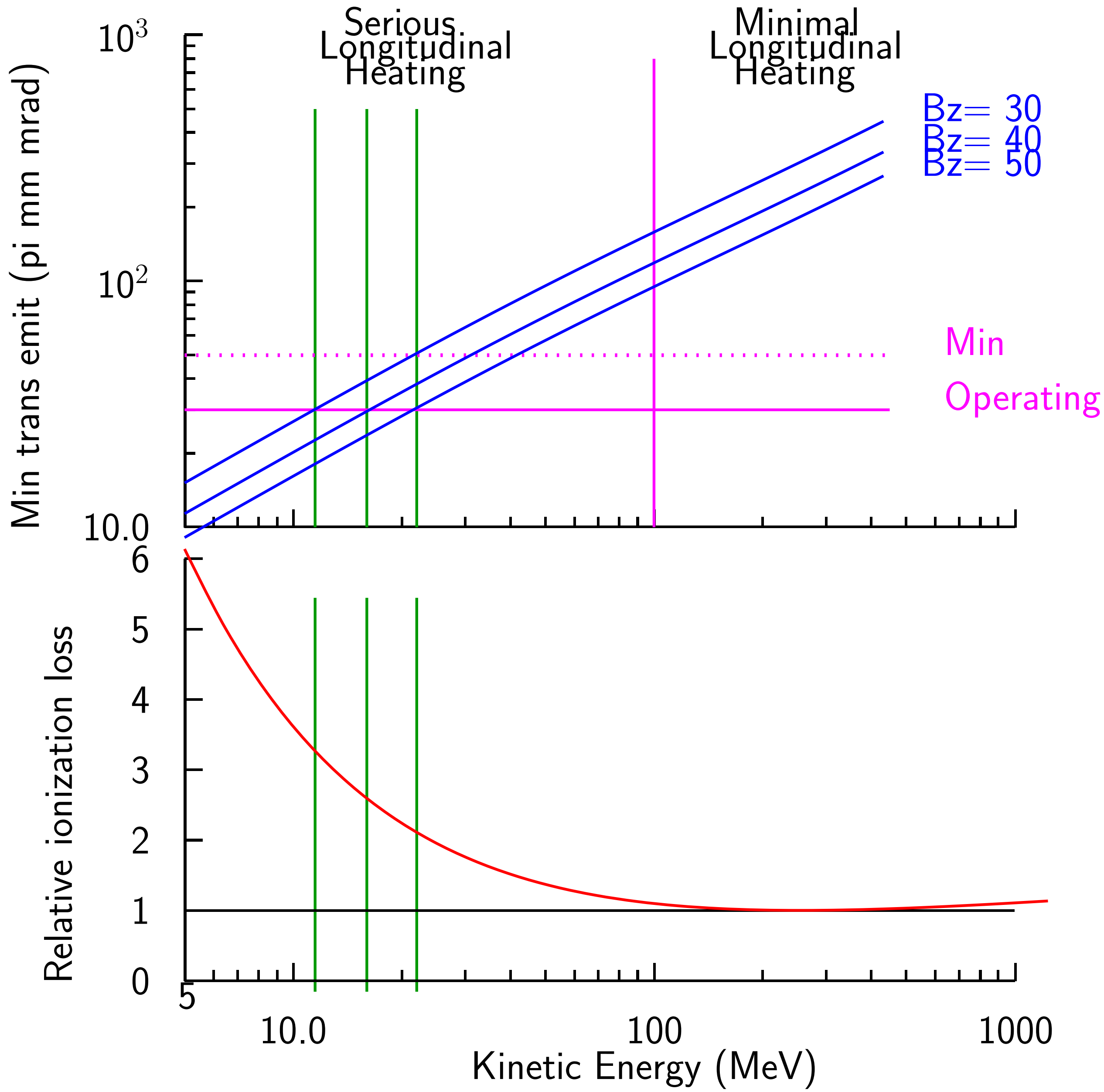


- YBCO superior to 2223 BCCO
- Current densities can be VERY high (> 1000 A/mm^2)
- But seemed to be ok   will come back to this

Muon Collider final cooling requirements

- Lower Field Requires lower energies
- Lower energies face faster growth of loss
- Faster increase in dp/p
- Greater Long emit increase
- May not be accepted by Collider Ring

- 50 T is good
- 40 T may be acceptable
- 30 T probably not



Magnet requirements for final cooling

Number of magnets	≈ 20	More if field is lower
Lengths	$\approx$ 1m at start	$\approx$ 10 cm at end
Beam sigmas	4 mm at start	0.7 mm at end
Minimum magnet bore	2 cm at start	1 cm at end
Field Quality	very loose	very loose

BNL/PBL SBIR Program

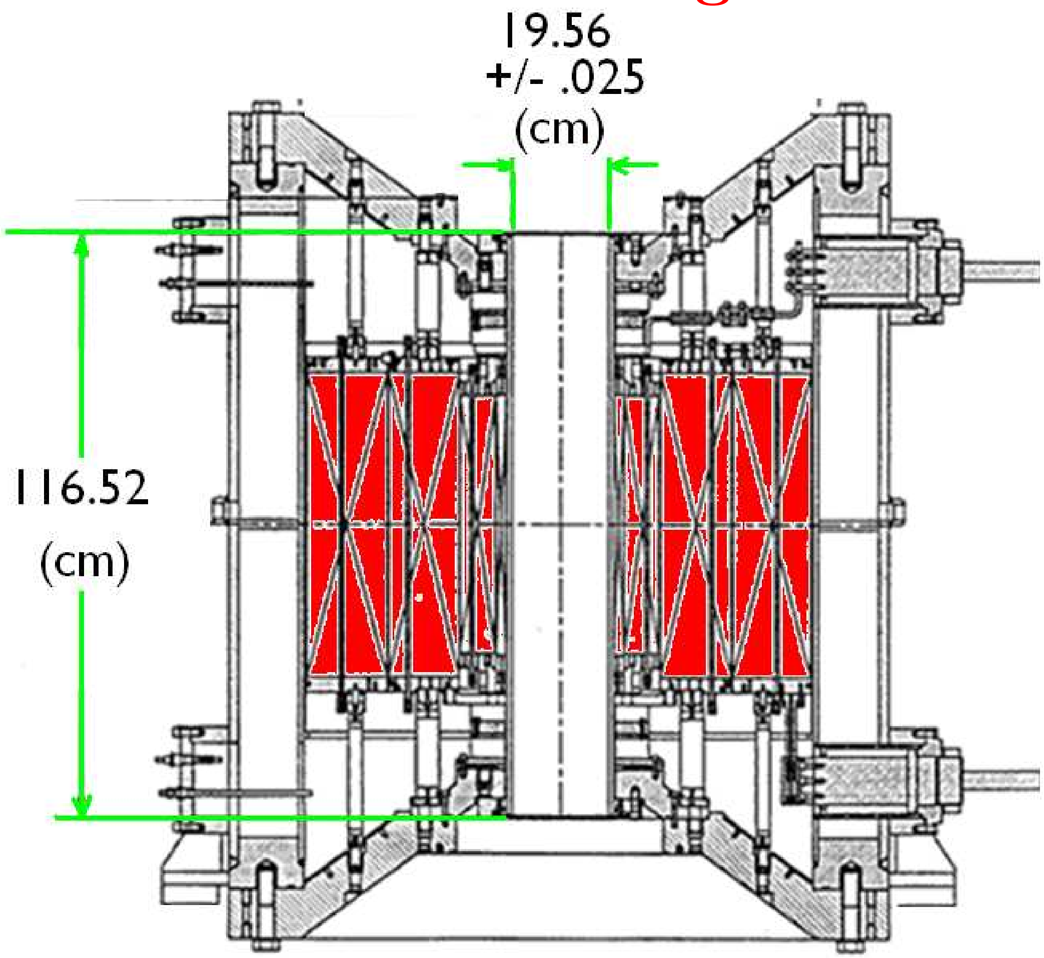
- First phase 2 SBIR:
  - Study 6D cooling using 10 T solenoids
  - Build 10 T Solenoid   10 cm diameter bore
  - Chose to use YBCO to explore very high current densities $\rightarrow$ compact
- Second phase 2 SBIR:
  - Study final cooling in 40-50 T solenoids
  - Build 12 T YBCO Solenoid   2.5 cm diameter bore that fits inside #1
  - Test both solenoids in 19 T magnet at NHMFL
- Final field calculated $\rightarrow$ 40 T, but this is R&D. Nothing is guaranteed
- The Wilsonian approach: start building
- Current status
  - All YBCO tape finally arrived
  - 17 of 28 pancakes of first magnet wound
  - Testing started

Some details

	Length mm	Inside diam mm	Outside diam mm	Stand alone field T
NHMFL Resistive	595	233	1010	19
YBCO #1	128	100	165	10
YBCO #2	64	25	95	12

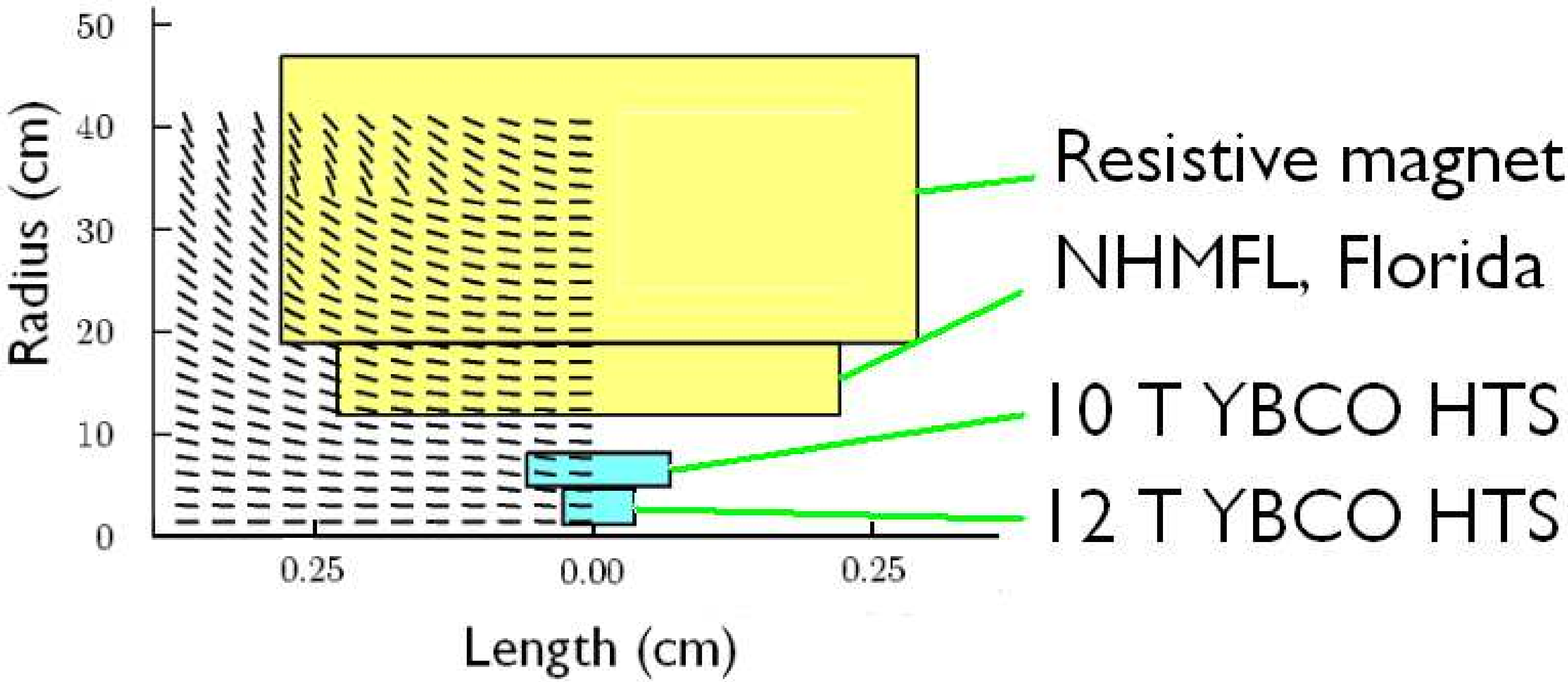
- YBCO width ≈ 4 mm
- YBCO Thickness ≈ 100 microns
- Length per pancake for #1: ≈ 100 m
- Length per pancake for #2: ≈ 50 m
- Insulation: 25 micron stainless steel tape
- Wound dry with conductor and insulation 'in hand'
- Pancake 'painted' with epoxy to allow handling Not vacuum impregnated
- Splices, as needed, in winding
- Splice pancake to pancake at center using 8 mm tape
- Voltage taps at center and 4 spaced through coils

NHMFL 19 T Resistive magnet



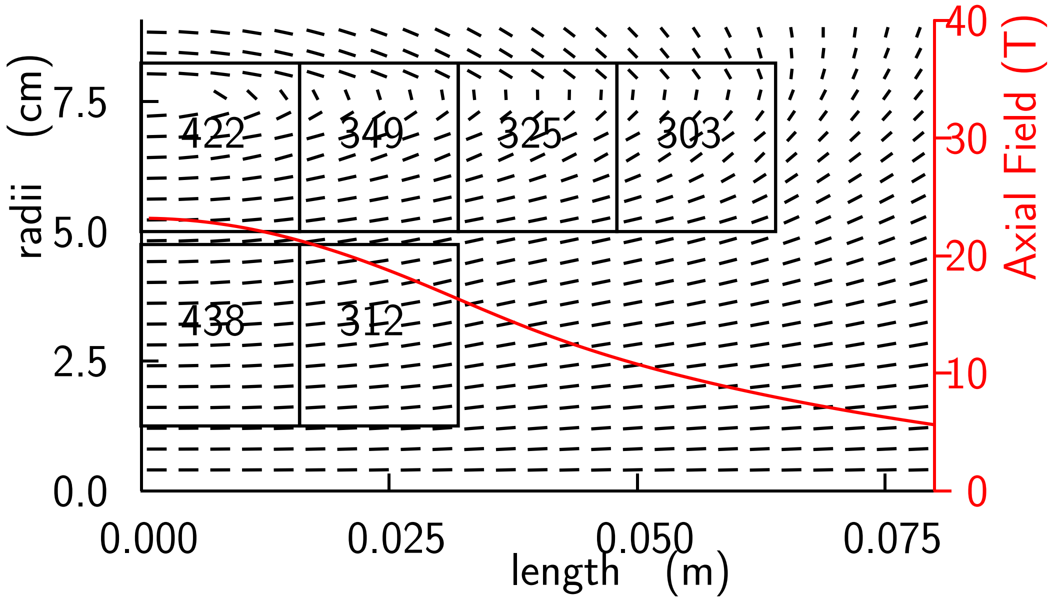
- 19.5 cm dia. bore
- They have cryostat that we can use
- Uses $\approx$ 20 MW
- A superconducting magnet with these parameters commercially available

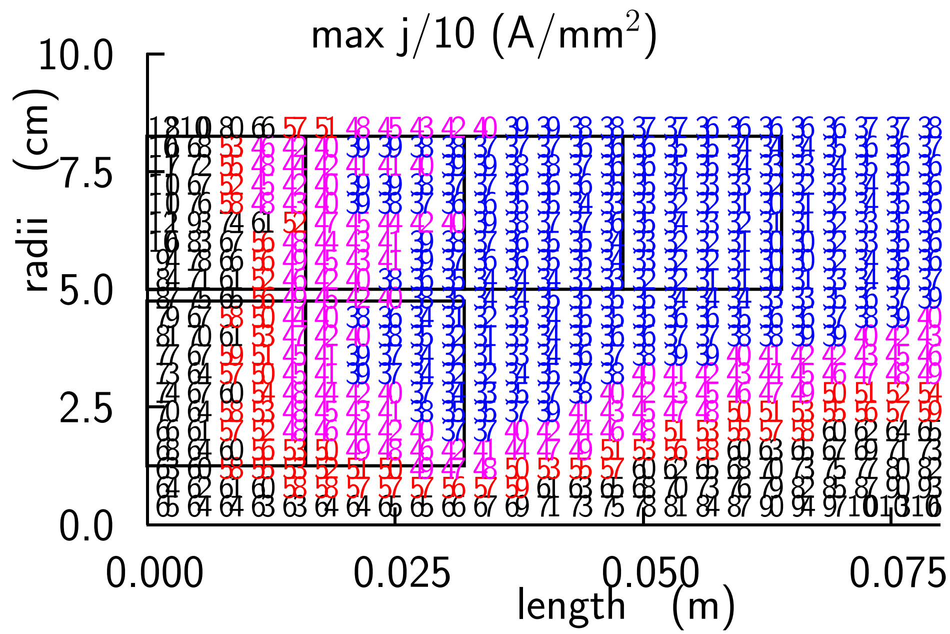
HTS magnets in 19 T Resistive



- Nominal Fields: $10 + 12 + 19 = 41$ T
- But we must calculate using field and angle dependent densities

Maximum performance without resistive magnet

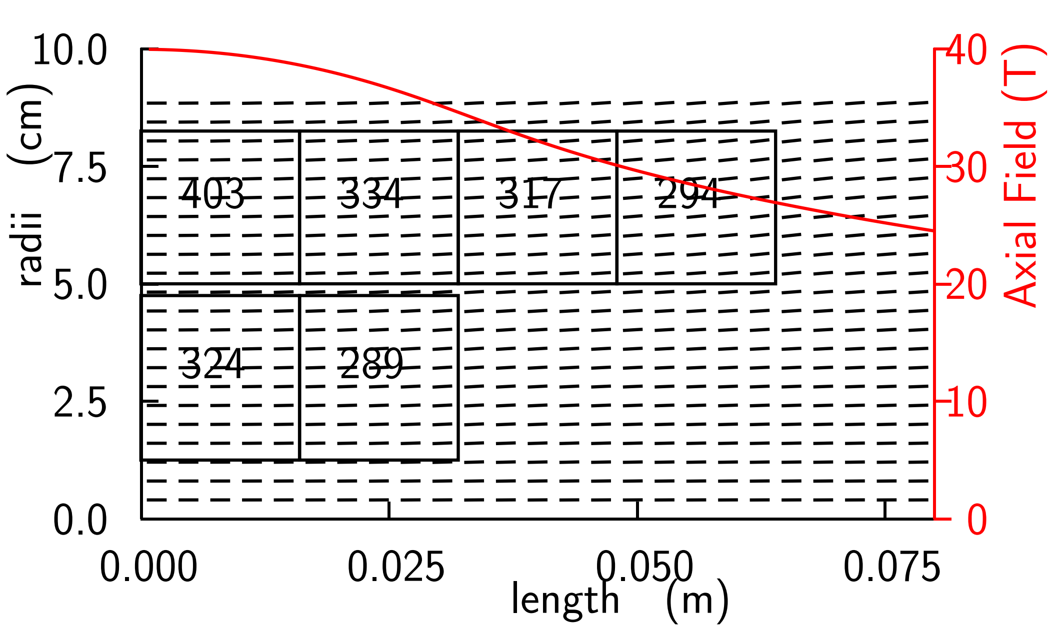


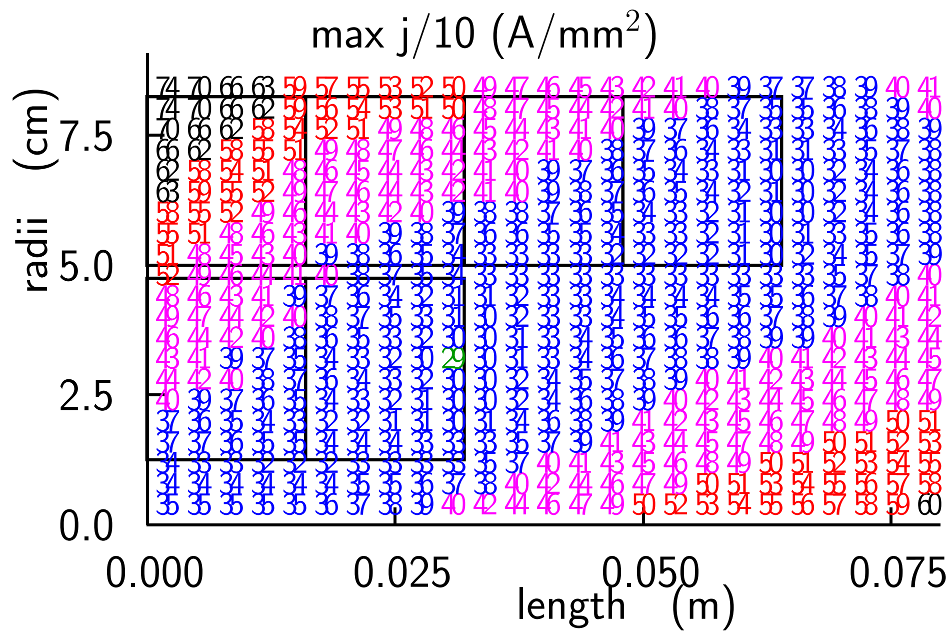


- Maximum current densities calculated from field and angles
- Current densities kept just below these for each of 12 blocks
- No margin included

		graded	not graded
Central Field	T	22.4	18.8
Maximum current density	A/mm^2	425	321
Maximum Stress	MPa	235	155

Maximum performance with resistive magnet





- Maximum current densities calculated from field and angles
- Current densities kept just below these for each of 12 blocks
- No margin included

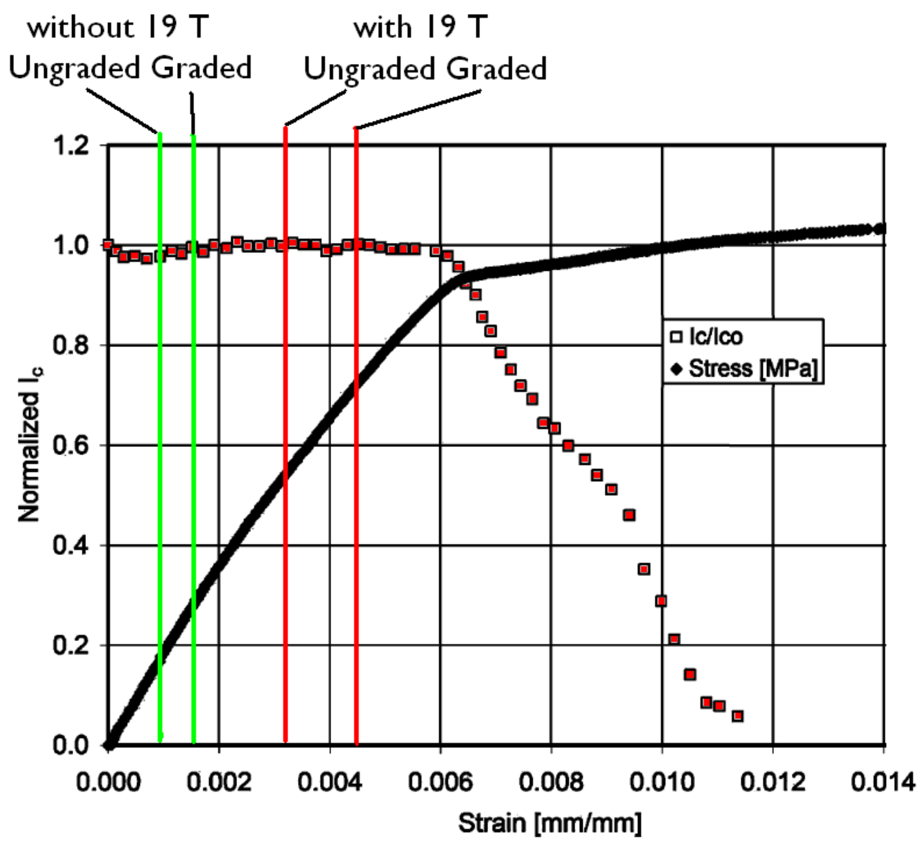
		graded	mod graded	not graded
Central Field	T	39.9	39.8	38.0
Maximum current density	A/mm^2	400	344	294
Maximum Stress	MPa	661	568	487

Strains and their consequences

- Maximum hoop stresses are in outer coil
- Young's modulus of HTS tape: 140 GPa
- Young's modulus including stainless insulation:

$$E = \frac{100\ 140\ +\ 25\ 200}{125} = 152\ \ (\mathrm{GPa})$$

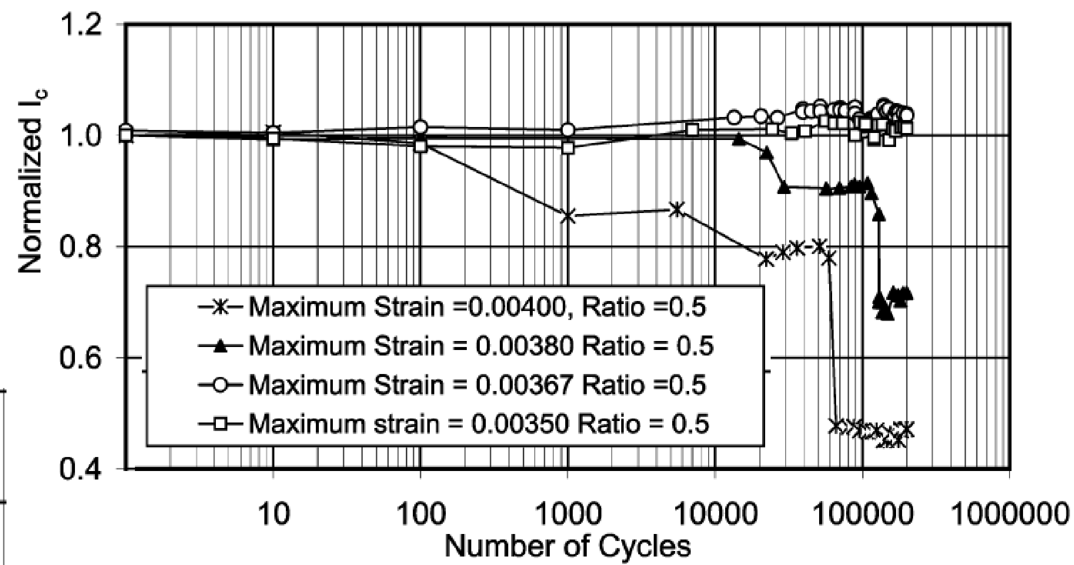
Case	Field T	Stress MPa	Strain %
Without 19T ungraded	18.8	140	0.09
Without 19T graded	22.4	232	0.15
With 19T ungraded	38.0	473	0.31
With 19T graded	39.9	661	0.44
With 19T mod grad	39.8	568	0.37

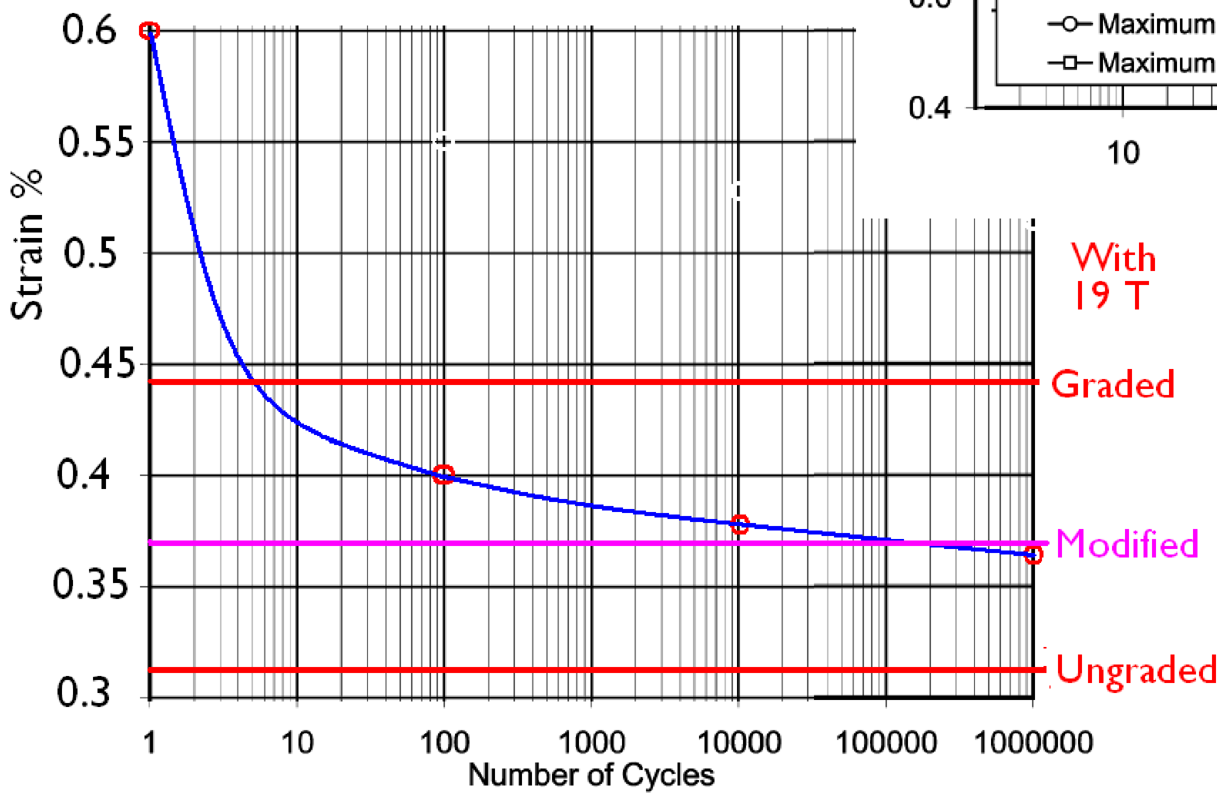


- Strains are higher when the currents in the coils are graded
- Strains appear well below levels causing loss of performance
- And are below manufacturer's recommended limit of 0.45 %

But fatigue is an issue

Fatigue Behavior of YBaCuO/Hastelloy-C Coated Conductor at 77 K Abdallah L. Mbaruku and Justin Schwartz

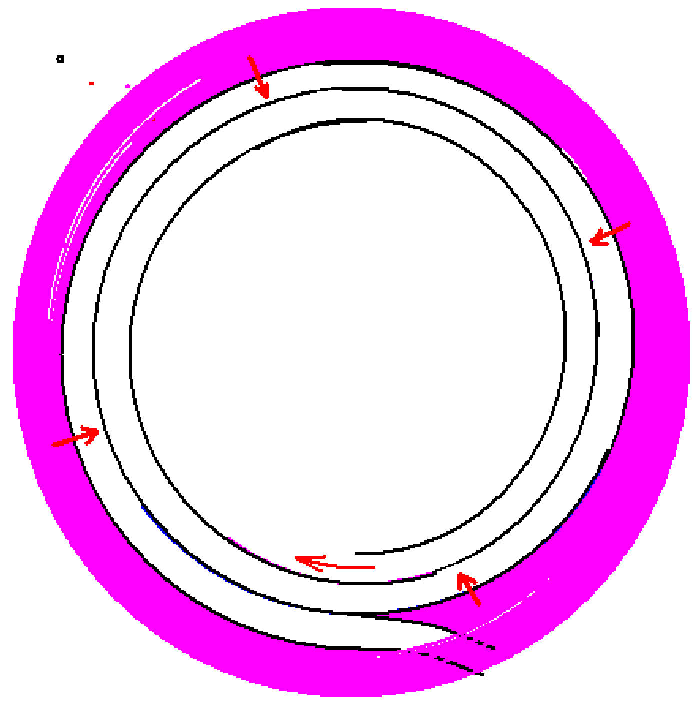




- Stainless steel tapes should be thicker in real magnet for graded case
- Probably ok for this test with limited number of operations

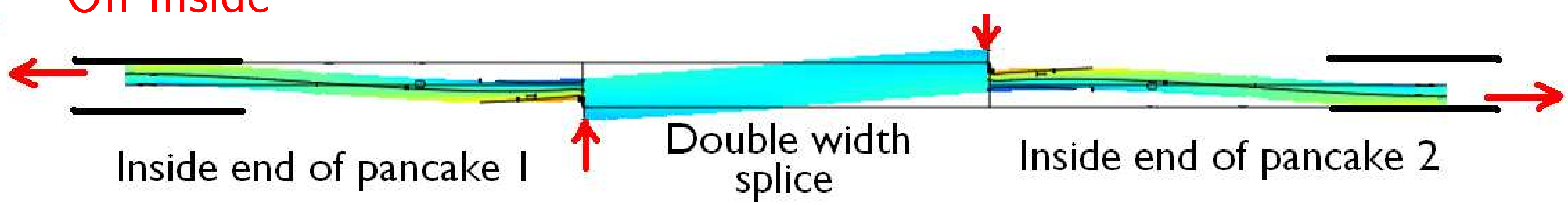
Constraints of tension in tapes

On outside



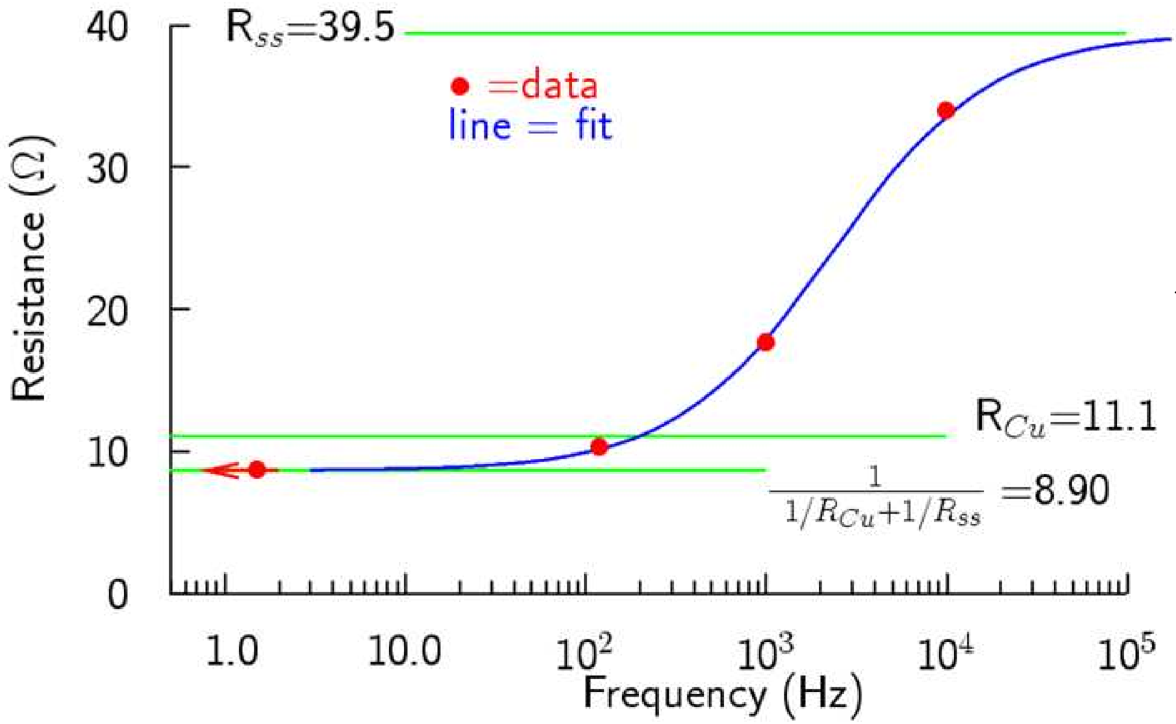
- Turns are under tension to hold Lorenz forces
- This tension must be transfered between 2 coils of pancake
- Can be done on outside by friction between compressed turns below overwrap

On Inside



- On inside, splice is pulled skew by tape tensions
- Spice must be long
- Must be constrained on either side

Measurement of stainless steel 'Insulation'



$$R(f) = \frac{1}{\frac{1}{R_{ss}} + \frac{1}{R_{Cu}+L\times f}}$$

- Measure impedance vs. Frequency
- Impedance through copper in tape increased with frequency
- Impedance through ss does not

- Fit gives resistance through ss, per pancake, of 39.5 ohms

Quench Protection

For temp rise < 200 K, and RRR=50 (including magneto resistance)

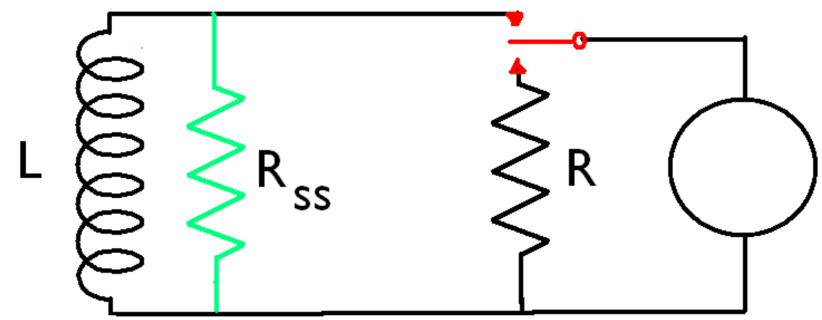
$$\int j^2 \, dt \; < \; 10.6 \; 10^{16} \qquad (Am^{-4}s)$$

Cu thickness 40 μm Total thickness 125 μm $j_{Cu} = 3.125 \; \times \; j$

The required time constant is

$$\tau \; = \; \frac{2 \; 10.6 \; 10^{16}}{j_{Cu}^2}$$

The external shunt resistor needed



$$R \; = \; \frac{L}{\tau} \qquad\qquad L \; = \; 2 \; U/I^2$$

Getting the inductance L from the ungraded example

U=80 kJ, and $I = j \; t \; w \; = \; 320 \; 4.4 \; 0.125 \; = \; 176$

Parameters for Quench Protection

Case		j	j_{Cu}	τ	R	$< I >$	V
		A/mm^2	A/mm(max)^2	sec	Ω	A	kV
without 19 T	ungraded	321	1003	0.21	24	176	4.3
	graded	425	1328	0.12	43	197	8.5
With 19 T	ungraded	294	918	0.25	20.5	166	3.4
	graded	400	1250	0.13	38	180	6.8
	modified	344	1075	0.18	28	178	5.0

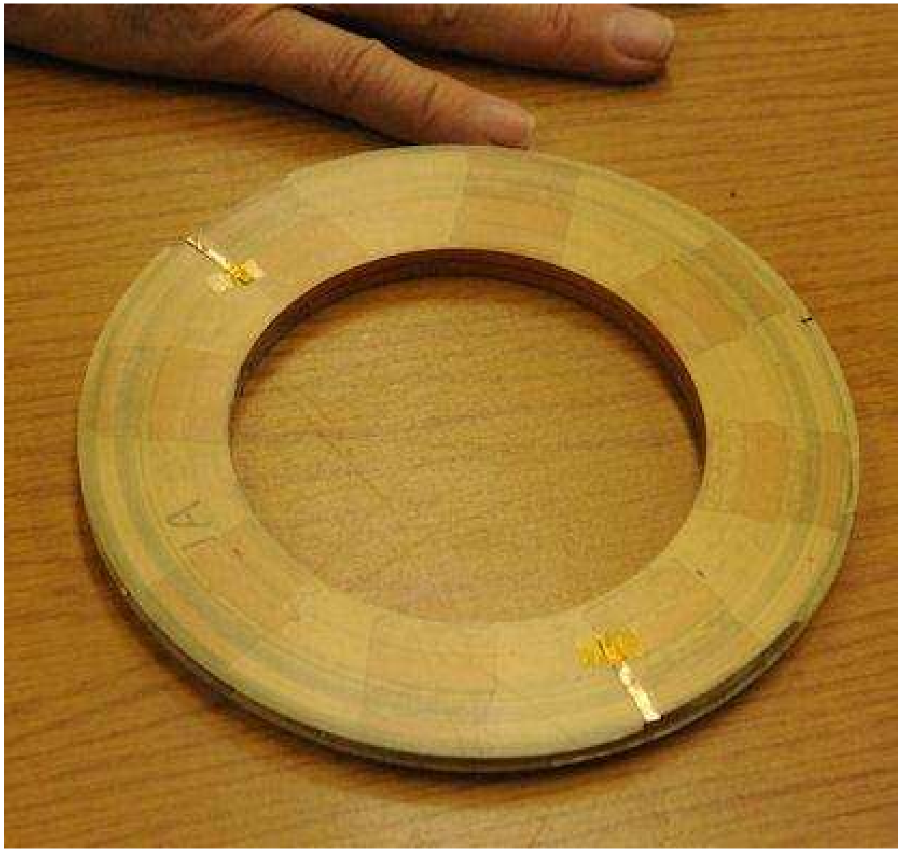
High current densities in the copper $\rightarrow$ short time constants

In all cases, the external resistor is small compared with the leakage resistance through the stainless steel insulation of $\approx (28+14/2)39.5 =$ 1380 ohms
So a negligible part of the energy is dumped in the ss insulation

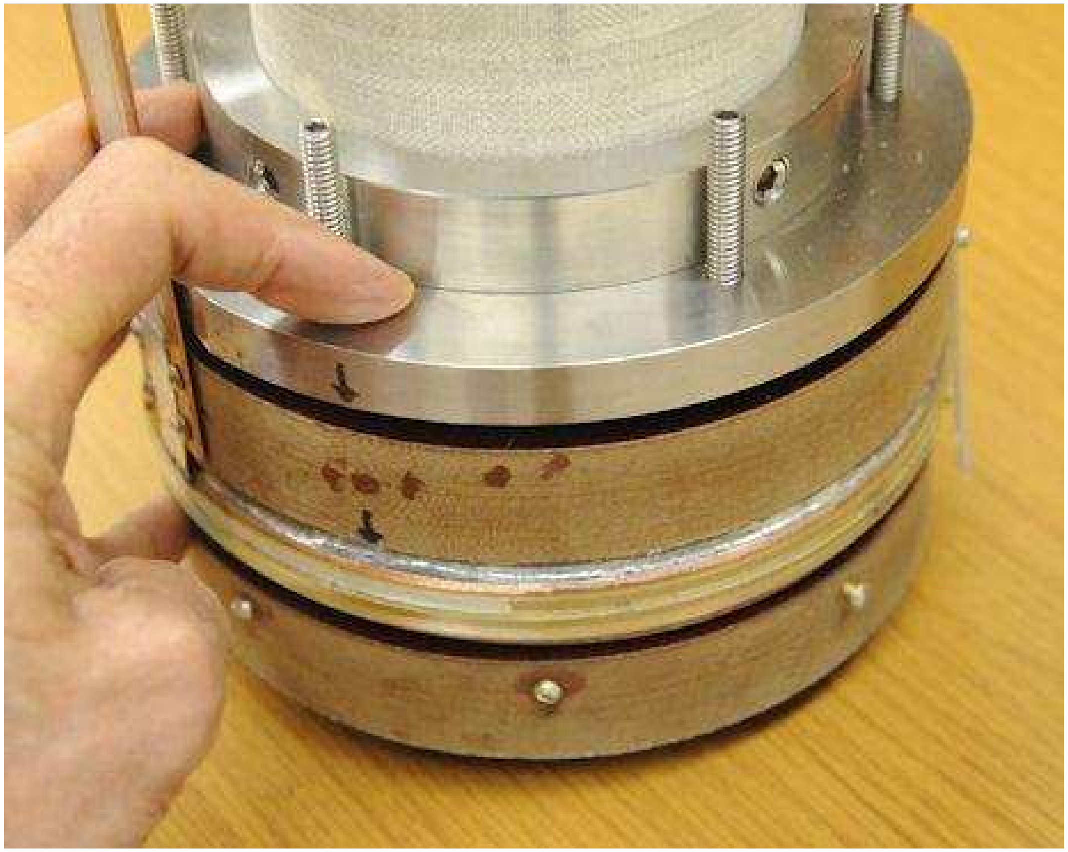
The above voltages are calculated for all coils in series. But multiple quench protection circuits are needed. e.g for 12 blocks: V $\leq$ 770 Volts

Having multiple circuits does not change the calculated ratios of stainless steel resistance to external resistors

Progress and coil tests

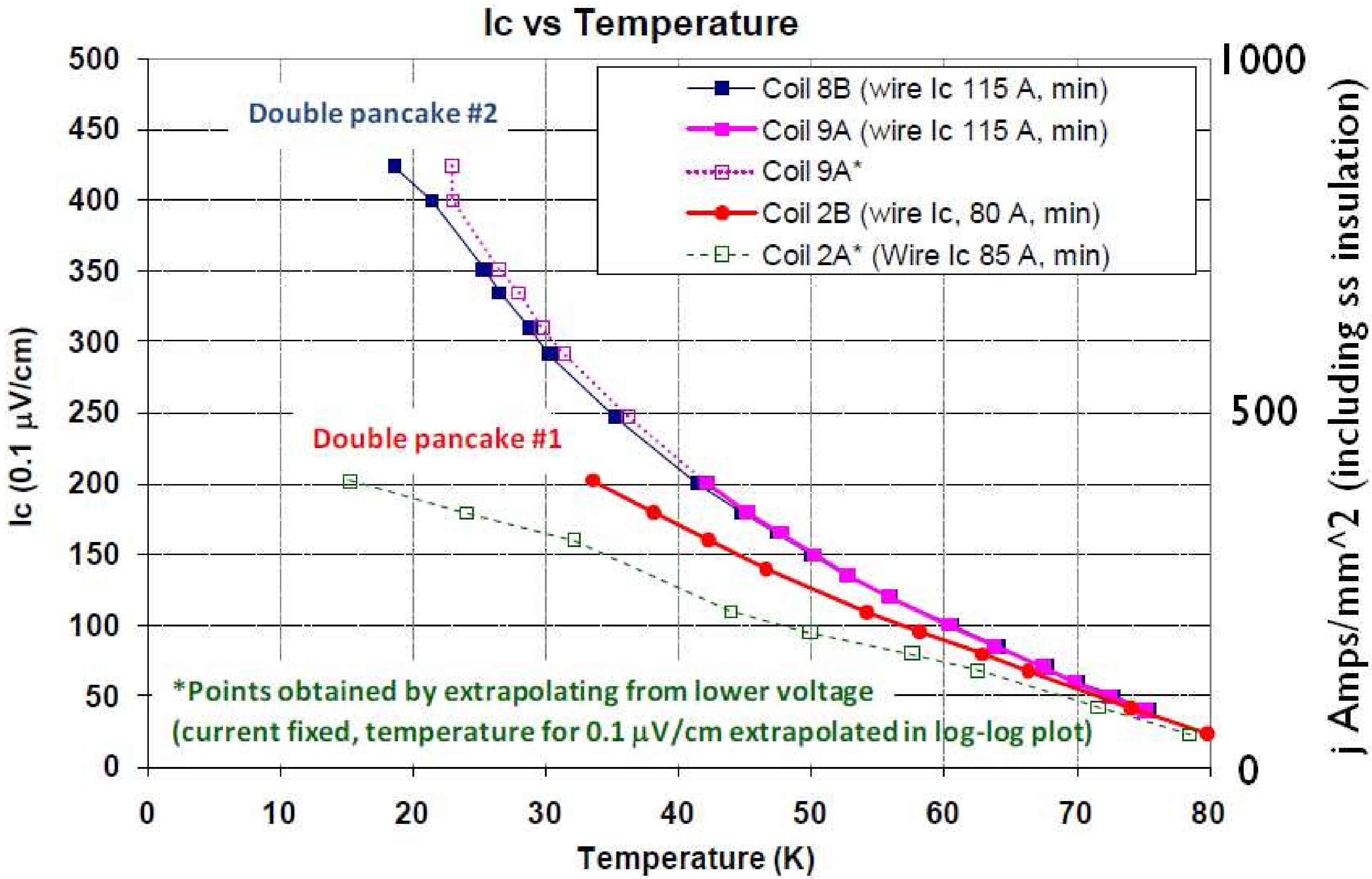


Single pancake



testing assembly

Test of 2 double pancakes



- One pancake of #1 appears damaged   probably during a previous 'quench'
- Current density in test is very high   though lower than in RIA/FRIB test
- Quench protection is probably needed

Safe time constant $\propto\ 1/I^2$ For 400 A j_{Cu}=2780 (A/mm^2) τ=27 msec

Conclusion

- YBCO has significantly better performance than BCCO
- Magnetization probably prohibits its use in accelerator magnets but ok for Muon Collider final cooling
- Final cooling probably needs B$\geq$ 40 T
- Two funded Phase II BNL/PBL SBIRs are exploring YBCO use at fields approaching 40 T, when tested in the NHMFL 19 T resistive solenoid
- Design study finds no show stopper, including
  - jc including angle effects
  - Strains in the conductor, including fatigue
  - Quench protection
  - Central field $\approx$ 40 T with worst conductor & 20% margin
- Progress
  - Required tape delivered
  - 17 (out of 28) outer pancakes wound
  - Preliminary testing of double pancakes started
- 40 T may not be achieved in this magnet, but 'Wilsonian' approach should provide useful information